REFINEMENT OF THE CLASSIFICATION OF LUNAR MARE BASALTS USING THE ABUNDANCES OF FeO, TiO_2, AND OLIVINE.

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We are refining Pieter's [1] global classification of mare basalts by determining the FeO and TiO_2 contents and relative abundance of olivine of mare units mapped by her, using techniques developed recently [2,3,4,5]. We have also constructed a GIS data base that includes the nearside geologic map and the concentrations of FeO and TiO_2. Our analysis of these data indicate that there is a range in the FeO content of mare lava flows, from about 13 to 20 wt.%. The low FeO areas are confined to Maria Nectaris and Orientale.; both are low in TiO_2. These maria are low in olivine, so are probably not ultramafic, magnesian lavas; they are more likely to be richer in plagioclase (hence, Al) than other mare basalts. The highest FeO concentrations are found in the western maria, especially in mare units near Flamsteed. Other maria are intermediate in FeO (15-18 wt.%). TiO_2 ranges widely and continuously from low values of 0.6 up to regions with apparent concentrations between 15 and 20 wt.%. The highest TiO_2 flows are found in Mare Tranquilitatis, in units mapped as vh-A by Staid et al. [6]. These flows are candidates for being differentiates of magmas similar to picritic glasses very high in Ti [7]. Olivine-rich basalts include the Flamsteed lavas and the prominent young flows in Imbrium. Our data are completely consistent with the spectral properties on which the original classification was based.

Original classification and new approaches

One of the earliest comprehensive classification method was established by Pieters [1] where 13 mare basalt types and three additional volcanic groups were mapped based on UV/VIS ratio, albedo, 1 µm and 2 µm band strength. Multispectral imagery and albedo maps were used to define unit boundaries. The telescopic spectral imagery used had a spatial resolution of 1-50 km with 2-4 band passes between .38 and 1.0 µm. Telescopic reflectance spectra of varying spatial and spectral resolution were used for the .3 to 2.1 µm region. The albedo maps have a nominal spatial resolution of 3 to 6 km. This classification was very useful, but because it did not include quantitative chemical information, it was often difficult for anyone not intimately familiar with reflectance measurements to make consistent and coherent use of it for understanding the petrogenesis of mare basalts and their mantle source regions. New data and analysis techniques are now available, however, so we can revisit the classification scheme and attempt to quantify it.

Most of the data for this effort comes from Galileo and Clementine data sets. Galileo on the second lunar pass utilized the solid-state multispectral imaging system (SSI) with 7 filters with an imaging resolution of up to 1.1 km [8]. Clementine had a UV-VIS imager with 5 spectral bands ranging from .415 to 1.000 µm. The data was initially subsampled to 35 km spatial resolution and the up to 200 m spatial resolution will be utilized in selected areas as it becomes available [9]. The spectral reflectance data from these missions have been calibrated to give FeO and TiO_2 wt % with errors of less than 0.5% [2,3,4]. In addition, Lucey et al. [5] used near-IR data (1.1 to 2.7 microns) obtained from Mauna Kea Observatory and developed a technique to estimate the abundance of olivine on the lunar surface. At present the method allows us to categorize flows as having low olivine abundances (olivine/pyroxene <0.2) and high abundances (about equal amounts of olivine and pyroxene).

Results

We utilized GIS masking techniques to isolate the mare regions for this study. The three major mare units (Im, Em, Emp) on the 1971 Wilhelms and McCauley [10] 1:5M lunar nearside geolologic map were used to isolate areas on the FeO and TiO_2 images. This technique minimizes the effects of highlands mixing in the boundary areas.

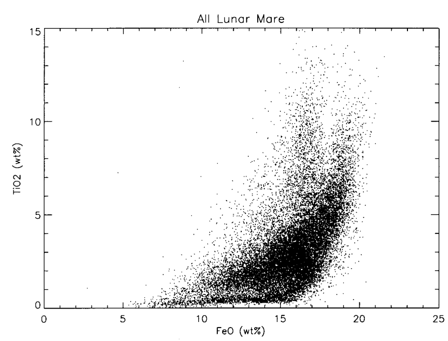

Fig. 1

The figure above shows a distribution of FeO and TiO_2 for all mare areas on the nearside. The data has been subsampled for legibility. It shows two FeO trends from mid to high TiO_2 in the upper right. The TiO_2 is fairly continuous with no gap between high and low values. When these lobes are correlated with the map it shows that the left lobe is derived from Mare Tranquillitatis and the right lobe eminates from the western limb. The bulk of the mare material is characterized by the large cluster between 14-17 wt. % FeO and 1-4 wt. % TiO_2.

To quantify the remote sensing classification of mare basalts [1], we identified all units in the classification on images of FeO and TiO_2. The areas were examined carefully and fields of interest were chosen that represented the units with no mixing from nearby highlands or other mare units. For simplicity here we do not list ranges or standard deviations. The latter were typically 5 to 10% relative to the amount present. The FeO and TiO_2 contents of the mapped units are given in Table 1, along with the olivine abundance (low or high). Tranquilitatis units are those observed by [6]. We also give the composition of other units near the type areas when they differed significantly from the type unit, but had not been mapped before. The range in FeO observed in Fig. 1 is seen here also: Flamsteed is distinctly higher in FeO than the other mare units. At the other extreme, Nectaris is quite low in FeO. In fact, the area chosen for our average composition is at the southern end of the maria, where values are higher than in the northern end. Nectaris is low in olivine, so its low FeO is not caused by an exceptionally magnesian composition (which would probably be rich in olivine). More likely, the basalts there are as ferrous as elsewhere, but more feldspathic. This is consistent with Pieter's [1] observation that they have average 1-micron bands, which indicates pyroxene with high FeO. Most of the maria are intermediate in FeO, ranging from about 15 to 18 wt.%. This range in FeO further demonstrates that the lunar mantle was very heterogeneous when mare basalts were forming. Mare Tranquilitatis is quite complex, as shown by Staid et al. [6]. Our results are generally consistent with theirs. The most striking feature of Mare Tranquilitatis is that some areas contain very high concentrations of TiO_2. Staid's unit vh-A has the typical FeO content of about 17 wt.%, but TiO_2 reaches as high as 20 wt.%. We find that most of unit vh-A has TiO_2 of 14 wt.%, though it ranges down to 10 wt.%. This is an excellent candidate for a magma similar in composition to a pristine picritic glass composition that fractionated, either along the flow or in a magma chamber during the interval between successive eruptoins. As Longhi [7] has shown, high-Ti picritic compositions would fractionate olivine, increasing TiO_2 from 13 to 15 wt.% (red glass) or from 16 to 17 wt.%, before ilmenite crystallized and TiO_2 began to decrease. The few spots of possibly even higher TiO_2 could be places where ilmenite accumulated during fractionation inside a flow. This area clearly demands detailed study.

[1] Pieters (1978) *Proc. Lunar Sci. Conf. 9th*, 2825-2849. [2] Lucey, P. G. *et al.* (1995) *Science*,**268**, 1150-1153. [3] Blewett, D. T. *et al.* (1996) *LPSC XXVII*, 781-782. [4] Blewett, D. et al. (1997) This volume. [5] Lucey, P. G. et al. (1997) This volume. [6] Staid, M. et al (1996) *J. Geophys. Res.* **101**, 23,213-23,228. [7] Longhi, J. (1992) *Geochim. Cosmochim. Acta* **56**, 2235-2251.; *LPI Tech. Rpt. Number 90-02m 46-47*. [8] Belton, M. J. S. *et al.* (1994) *Science*, **264**, 1112-1115. [9] Nozette, S. *et al.* (1994) *Science*,**266**, 1835-1839. [10] Wilhelms, D. E. and McCauley, J. F. (1971) *Geologic Map of the Near Side of the Moon*, USGS/Department of the Interior.

Table 1. Units from [1,6] and data from this work.

Unit Designation	Type Area	FeO (wt %)	TiO_2 (wt %)	Olivine (relative)
HDSA	Flamsteed (Ring)	20	10	high
HDWA	Apollo 11			
	vh-A	17	10-20	low
	h	17	3-8	low
	vh-B	17	5-13	low
	l	16	1.5-5	low
hDSA	Imbrium (Blue)	18	5.2	high
hDW-	Luna 16	16	4.8	low
		15	7.8	low
		16	3.2	low
hDSP	Mare Humorum, NE	18	4.7	--
		18	7.1	--
hDG-	Nubium	17	4.9	--
mISP	Serenitatis	17	2.1	
mIG-	Apollo 12	17	3.5	low
	So.Imbrium	14	2.0	low
mBG-	Nectaris	13	1.9	--
LIG-	Apollo 15	16	1.0	low
LBG-	Somniorum	15	0.7	low
LIS-	N. Crisium	15	1.5	low
	A-12in Crisium	16	2.7	low
LBS-	Frigoris	16	0.5	low